Status of earth observing system Terra and Aqua moderate-resolution imaging spectroradiometer level 1B algorithm

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Abstract. The first MODerate-resolution Imaging Spectroradiometer (MODIS) was launched on the Terra spacecraft on December 18, 1999. The second MODIS was launched on the Aqua spacecraft on May 4, 2002. As an integral part of NASA's Earth Observing System (EOS), these instruments provide daily observations of nearly the whole Earth with the goal of enhancing scientific characterization of land, ocean, atmosphere, climate change, and natural hazards. MODIS uses a scanning mirror, 490 detectors distributed among 36 spectral bands, and on-board calibrators (a solar diffuser, solar diffuser stability monitor, a blackbody, and a spectro-radiometric calibration assembly) to meet these objectives. The MODIS Level 1B (L1B) algorithms, written in C, input uncalibrated, geo-located observations, convert the instrument response into calibrated data, and generate science data sets. This calibration is performed on a pixel-by-pixel basis for each detector. The instrument characterization needed to run the L1B code is implemented using 96 Terra and 99 Aqua Look-up Tables. This paper describes the current L1B algorithm and discusses the changes made as a consequence of on-orbit analyses and operational considerations.

Keywords: MODIS, Terra, Aqua, remote sensing, L1B algorithm.

1 INTRODUCTION

The MODerate Resolution Imaging Spectroradiometer (MODIS) is the keystone instrument on NASA's Terra and Aqua satellites. Each of the two Earth-orbiting MODIS instruments provides nearly global coverage daily in support of land, ocean, and atmospheric studies. MODIS has 490 detectors distributed among 36 spectral bands covering spectral regions from the visible (VIS) to the long-wave infrared (LWIR). Bands 1-19 and 26 are the reflective solar bands and the others are thermal emissive bands. Observations are made at 250m, 500m, and 1km nadir spatial resolutions. Detailed descriptions of the MODIS bands are available [1,2].

The sensors' raw data are transmitted to ground stations through Tracking Data Relay Satellite System (TDRSS) contacts and sent to the EOS Data and Operations System (EDOS). Large volumes of MODIS binary data files are ingested by the MODIS Adaptive Processing System (MODAPS). This Level 0 data is reformatted and geo-located into Hierarchical Data Format (HDF) Level 1A files consisting of 5 minute segments (or "granules"). Normally, each granule comprises 203 or 204 scans of the two-sided, rotating MODIS mirror. The

MODIS Characterization Support Team (MCST) is responsible for the development, maintenance, and improvement of the Level 1B (L1B) software that converts the geo-located raw instrument data numbers (DN) into top of the atmosphere (TOA) calibrated radiances for all bands and into reflectances for the 20 reflected solar bands (RSB). L1B calibrates each pixel, which are indexed by band, detector, sub-sample (for the sub-kilometer high resolution bands 1-7), and mirror side.

The unique operational configurations and characteristics of MODIS/Terra and MODIS/Aqua are handled by separate versions of the L1B software for each MODIS instrument. All changes to the software were tracked as the software evolved through several versions and major reprocessing "collections" in an effort to provide the best data products available at the time. The purpose of this paper is to describe the current and historic L1B algorithms and to illuminate the improvements made to each L1B collection as on-orbit data analysis led to improved instrument characterization.

Section 2 briefly describes the MODIS instrument. Section 3 provides an overview of the L1B algorithm and its early development. Section 4 discusses the improvements made to Terra and Aqua L1B collections 3 and 4. Section 5 presents the current collection 5 L1B software. Section 6 illustrates possible improvements for the next collection and highlights the lessons learned over the course of L1B development.

2 INSTRUMENT BACKGROUND

The MODIS design shown in Fig. 1 was predicated on earlier missions, primarily the Nimbus 7 Coastal Zone Color Scanner (CZCS), the Advanced Very High Resolution Radiometer (AVHRR), the High-resolution Infrared Radiation Sounder (HIRS), the Landsat Thematic Mapper (TM), and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). Each MODIS instrument uses 490 detectors arranged in 36 spectral bands to support the MODIS science objectives. Wavelengths range from 0.41 to 14.5μm. Bands 13 and 14 have high or low gain settings.
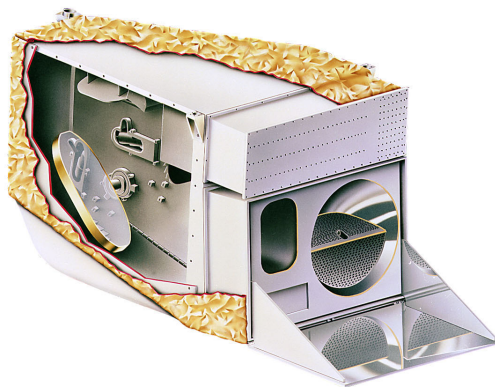

Fig. 1. The MODIS instrument.

MODIS has nadir geometric spatial resolutions of 250m (bands 1-2), 500m (bands 3-7) and 1 km (bands 8-36) and a ±55 degree swath using a flat paddle-wheel scan mirror. Three on-board calibrators (a solar diffuser combined with a solar diffuser stability monitor, a spectral radiometric calibration assembly, and a blackbody) provide in-flight calibration. The MODIS scan cavity schematic is illustrated in Fig. 2.
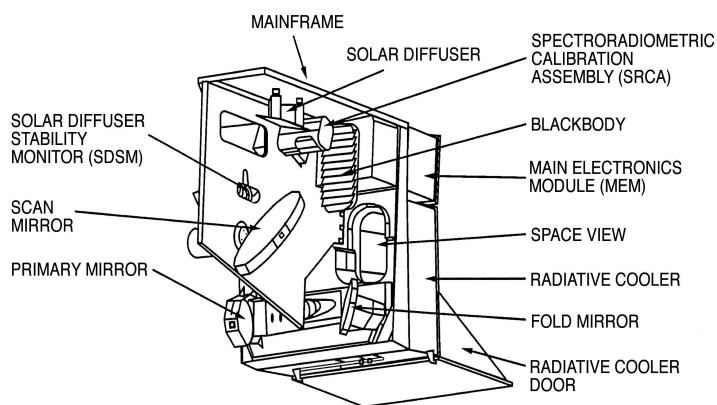
Fig. 2. MODIS scan cavity and on-board calibrators.

Table 1 provides measured characteristics for MODIS Terra and Aqua. The table provides data for both the 20 Reflective Solar Bands (RSB) and the 16 Thermal Emissive Bands (TEB). The Terra Signal-to-noise ratio (SNR) at typical spectral radiance in $W/(m^2*\mu m*sr)$ (Ltyp) and noise equivalent delta temperature (NEdT) at typical temperatures are provided using solar diffuser observations for the initial on-orbit operational configuration (initial Terra electronics side A, Aqua side B).

Table 1. Terra and Aqua MODIS measured characteristics.

RSB BAND	Central λ Terra, Aqua nm	Bandwidth Terra, Aqua nm	Terra SNR at Ltyp	Aqua SNR at Ltyp
1	646.3, 645.8	47.8, 47.2	177.7	186.2
2	856,5, 856.9	37.7, 37.8	466.1	492.9
3	465.7, 466.1	18.6, 18.8	312.0	308.8
4	553.7, 553.9	19.7, 19.6	315.9	310.7
5	1242.3, 1241.5	23.5, 22.8	97.3	138.7
6	1629.4, 1628.1	28.4, 26.9	346.9	362.5
7	2114.2, 2113.9	52.4, 52.3	104.1	148.6
8	411.8, 412.4	14.7, 14.3	1049.8	1089.5
9	442.1, 442.2	9.6, 9.6	1471.7	1499.9
10	487.0, 487.4	10.5, 10.6	1424.7	1513.5
11	529.7, 530.1	11.9, 11.9	1572.7	1676.1
12	546.9, 547.2	10.2, 10.3	1315.1	1479.5
13	665.6, 666.0	10.0, 10.0	1214.9	1415.2
13high	665.6, 666.0	10.0, 10.0	1293.3	1601.7
14	677.0, 677.6	11.3, 11.2	1374.4	1527.4
14high	677.0, 677.6	11.3, 11.2	1559.6	1896.3
15	746.6, 746.8	9.9, 9.8	1349.0	1510.2
16	866.3, 866.9	15.5,15.5	1119.0	1404.4
17	904.2, 904.4	34.7, 34.6	332.5	359.7
18	935.7, 936.4	13.5, 13.5	86.0	87.3
19	936.2, 936.3	45.7, 46.1	486.4	492.2
26	1382.3, 1382.3	34.6, 36.4	236.7	265.4

TEB BAND	Central λ Terra, Aqua nm	Bandwidth Terra, Aqua nm	Terra NEdT at Ttyp(K) (Terra A1)	Aqua NEdT at Ttyp(K) (Aqua B)
20	3788.3, 3780.2	187.5, 186.9	0.03	0.02
21	3992.2,3981.8	82.8, 83.3	0.15	0.21
22	3972.0, 3972.0	86.1, 85.4	0.02	0.02
23	4056.7, 4061.6	85.6, 85.3	0.02	0.02
24	4473.2, 4448.3	90.2, 92.2	0.13	0.11
25	4545.4, 4526.3	91.1, 90.4	0.05	0.04
27	6770.5, 6786.8	239.1, 187.9	0.10	0.10
28	7342.9, 7349.3	320.6, 314.9	0.05	0.05
29	8528.7, 8555.3	344.1, 359.2	0.02	0.02
30	9734.1, 9723.7	297.2, 301.1	0.11	0.07
31	11018.9, 11026.2	516.3, 531.1	0.03	0.02
32	12032.1, 12042.3	520.7, 521.5	0.04	0.03
33	13365.0, 13364.7	307.6, 310.9	0.13	0.08
34	13683.3, 13685.9	324.1, 341.7	0.23	0.12
35	13913.2, 13925.2	327.7, 332.7	0.23	0.15
36	14195.6, 14215.2	284.9, 327.9	0.43	0.23

The MODIS instrument characteristics and performance, a description of the current L1B versions, features of the science data products, and references to related documents can be found on the MCST home page [3]. Detailed information about the instrument can also be found [4,5].

3 L1B ALGORITHM OVERVIEW AND DEVELOPMENT

MODIS L1B algorithms provide radiometric calibration and are used to generate calibrated L1B science data sets. The L1B code was originally developed between 1993 and 1999. The L1B software ingests L1A and geo-located data, performs data monitoring and quality assurance, calibrates all detectors, transforms raw data numbers (DN) into radiances and reflectances, converts engineering counts into engineering units, produces the L1B data products, and creates and appends metadata. The operational software was designed to meet the objectives of being reliable, modular, portable, maintainable, and efficient.

Development milestones are presented in Table 2. As the calibration process developed, high-level code was written in Programming Design Language, operational modules were drafted, software requirements were adopted, and a preliminary design review was held. After implementing changes suggested at the review stage, a critical design review followed. Development continued using rigorous module review and unit testing. Finally, end-to-end tests were performed. Subsequent L1B updates followed a similar process. Complete regression testing of the code was always performed after each code change, and documentation was updated throughout the process. Validation was performed by MCST personnel and members of the MODIS Science Team.

Table 2. L1B algorithm development milestones.

L1B MILESTONE	DATE
Start Coding	1993
Beta 1 Heritage Delivery	January, 1994
Beta 2 Delivery (Demonstrate portability)	October 1994

Software Requirements Review	March 1995
Beta 3 Delivery (Exercise SDP Toolkit interfaces)	April 1995
Preliminary Design Review for version 1	June 1995
Critical Design Review for version 1	December 1995
Version 1 Delivery (All major functions, interfaces, messages)	March 1996
Preliminary Design Review for version 2	September 1996
Critical Design Review for version 2	December 1996
Version 2 Terra Launch-Ready Delivery	February 1997
Re-delivery of Version 2 (L1A and geo-location compatible)	September 1997
Pre-launch Code version 2.1.3	March 1999
Terra Post-launch Code version 2.3.2 (Collection 2)	March 2000
Terra Code version 3 (Collection 3)	May 2001
Aqua Code version 3 (Collection 3)	April 2002
Aqua Code version 4 (Collection 4)	October 2002
Terra code version 4 (Collection 4)	January 2003
Terra Code version 5 (Collection 5)	March 2005
Aqua Code version 5 (Collection 5)	July 2005

MCST uses Razor, a commercial off-the-shelf configuration management tool to track code versions and changes from 3/30/99 and beyond. Only one authorized person can check out the code at a time for editing and the reason for any change must be documented. Razor also is used to track major development issues. The MODIS project maintains a complete record of all L1B code releases used to produce data, including version number, source code, changes made since the last release and the reasons for those modifications, and documentation of the high-level design, unit testing and regression testing which accompanied each change.

The instrument characterization needed to run the L1B code is implemented using 96 Terra and 99 Aqua Look-up Tables (LUTs). These tables also provide updates that account for changes in sensor performance. LUT updates and changes are similarly tracked using Razor. Older L1B versions extending back to 9/30/97 are also available to MCST personnel.

The pre-launch version of the L1B code reached maturity in 1999. The code included realistic LUTs that produced reasonable radiances. Corrections were turned on or off as indicated by pre-launch analyses. The uncertainty algorithms were substantially revised. Additional quality assurance attributes were added and the file specifications finalized. Algorithms were upgraded to handle detector saturation and improve the calibration accuracy, notably in the short-wave infrared (SWIR) bands. All bugs identified during L1B independent verification and validation tests were corrected. Version 2 and subsequent versions of L1B were inserted in the processing path illustrated in Fig. 3. The browse images are an atmosphere team product produced at MODAPS.

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  │   LEVEL 1A CODE      │        │  LEVEL 1B LUT    │          ┌────▶│ LEVEL 1B OBC FILE      │
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  │    FILE (HDF)        │        │  CALIBRATION     │──────────┼────▶│ (MOD_PR02QA)           │
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  │    L1A FILE          │        ┌──────────────────┐                │ CODE (MOD_PR02BR)      │
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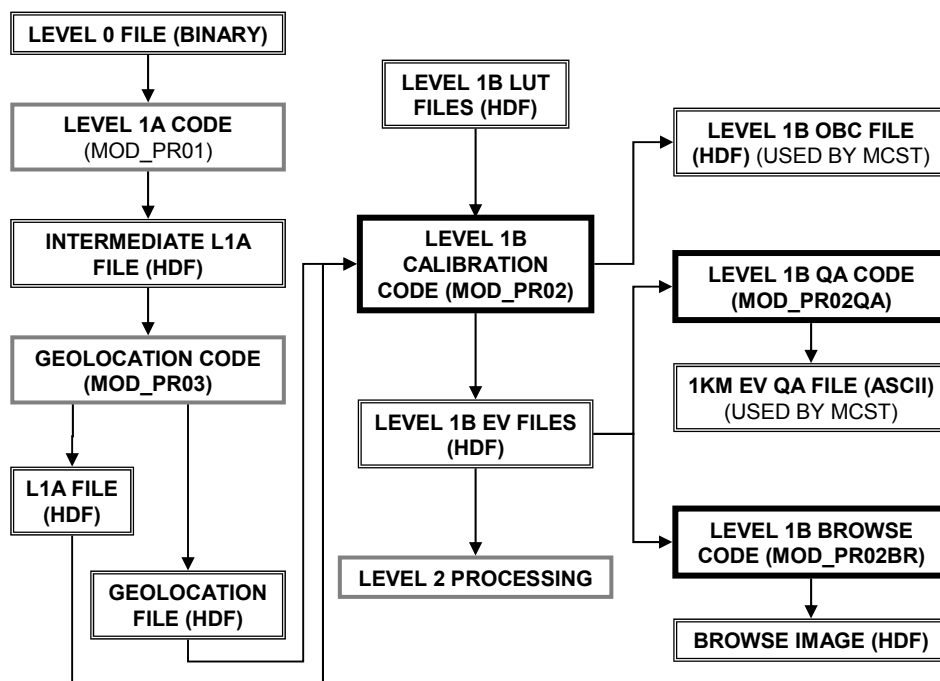
Fig. 3. Processing context of Level 1B code.

The first Terra post-launch code, placed into operations on 3/17/2000, was designated Terra version 2.3.2, where the first digit of the version number indicates the "collection". Between Terra and Aqua launches improvements were made to the Terra code. Post-launch collection 2 improvements were principally generated from analyses of on-orbit data. MCST paid special attention to calibration and LUT updates when key MODIS operational events (Tables 3 and 4) transpired. The small number of operational events beyond 2004 is a testament to the durability of the instruments and to the experience gained by the Flight Operations Team at NASA/GSFC.

Table 3. Key Terra MODIS operational events.

Date	Event Description
12/18/99	Terra launch
02/13/00	Science Mode, A-side electronics
02/24/00	First light; nadir aperture door open
06/08/00	Cold focal plane assembly stopped controlling temperature; ice forms
08/03/00	Focal plane assembly temperature set to 85K
08/05/00	Formatter reset anomaly; MODIS to standby mode, then safe mode
08/08/00	Outgas heater turned on for 2 days
08/19/00	MODIS returns to science mode
10/30/00	MODIS switches to B-side electronics configuration
05/20/01	Two MODIS solid state recorder supersets fail
06/15/01	Power supply 2 (PS2) B-side shutdown while in S. Atlantic Anomaly
06/20/01	Solid state recorder supersets recovered

07/02/01	MODIS switches to A-side electronics configuration using PS1
08/15/01	A-side formatter errors resume and increase over time
03/19/02	Spacecraft safe hold anomaly during maneuver
03/23/02	MODIS returns to science mode
09/17/02	Switch to B-side formatter; other components remain on A-side
05/06/03	Solar diffuser (SD) door fails to open when commanded
07/02/03	Solar diffuser door set to remain open with screen down
09/24/03	Solid state recorder shuts down and is re-enabled
10/14/03	Solid state recorder shuts down and is re-enabled
12/16/03	Attitude Control Electronics anomaly in SAA; S/C to safe mode
12/24/03	Nadir aperture door opened (transitioned to science mode 12/22/03)
02/18/04	Science Formatting Equipment (SFE-A) fails in SAA; data lost
02/19/04	MODIS returns to science mode
09/04/04	Loss of sync during solid state recorder playback over SAA; data lost
12/24/04	Science Formatting Equipment anomaly over SAA; data lost
08/26/05	Solid state recorder loses 2 supersets, is at limit of no-loss operations
08/22/06	Nadir aperture and SV doors inadvertently closed; lost 1 day IR data

Table 4. Key Aqua MODIS operational events.

Date	Event Description
05/04/02	Aqua launch
06/07/02	Science Mode, B-side electronics
06/24/02	First light; nadir aperture door open
06/27/02	Spacecraft in safe mode due to single event upset
07/02/02	MODIS returns to science mode
07/29/02	Spacecraft in safe hold due to spacecraft anomaly
08/06/02	MODIS returns to science mode
08/09/02	SD door open as command was accidentally dropped; door closed 08/14/02
09/12/02	S/C in safe hold due to ephemeris error; recovered fine pointing same day

4 IMPROVEMENTS TO THE L1B ALGORITHM

Terra and Aqua MODIS underwent extensive pre-launch radiometric, spatial, and spectral calibration and characterization activities. The problems identified and lessons learned from MODIS Terra calibration and characterization led to design and characterization improvements for Aqua. Although Terra and Aqua MODIS instruments are identical in many aspects, allowing a common calibration approach, variations in detector and instrument performance between the two instruments necessitate the adoption of similar but distinct L1B codes and LUTs. The codes and LUTs are individually maintained under a common configuration management system.

LUT contents are instrument dependent. Several LUTs are time dependent. Many pre-launch LUTs were updated and validated on orbit. The number of time-stamped table pieces for step function or piece-wise linear LUTs also vary between the two instruments. LUT histories are posted on the MCST Level 1B Product Information and Status web page and a spreadsheet of the number, characteristics, and purpose of all LUTs for each instrument is maintained. The complete code histories for MODIS/Terra and MODIS/Aqua are also posted to this site, http://www.mcst.ssai.biz/mcstweb/L1B/product.html.

MODIS/Terra and MODIS/Aqua LUT types are the same with one exception. Time-dependent LUTs specific to MODIS/Aqua are used to substitute scan-by-scan linear gains when thermal bands 33, 35, and 36 saturate. Saturation occurs when the on-board blackbody

is commanded to approximately 315K on a monthly basis to track system non-linearity characteristics in the thermal bands.

Both Aqua and Terra codes contain the capability to perform an optical cross-talk correction to Bands 32 - 36 using Band 31 data. This adjusts for the photons from Band 31 that leak into Bands 32-36 via the filter substrates. The correction is exercised only for Terra since the Aqua cross-talk is negligible. Such processing decisions are controlled through the LUTs.

Each new algorithm or proposed change to an existing algorithm was presented to the MODIS Science Working Group for approval and reported to the MODIS Science Team Leader. Major upgrades affecting calibration were signified by incrementing the L1B collection number by one digit. All MODIS data has been reprocessed for each collection to produce long-term data product consistency.
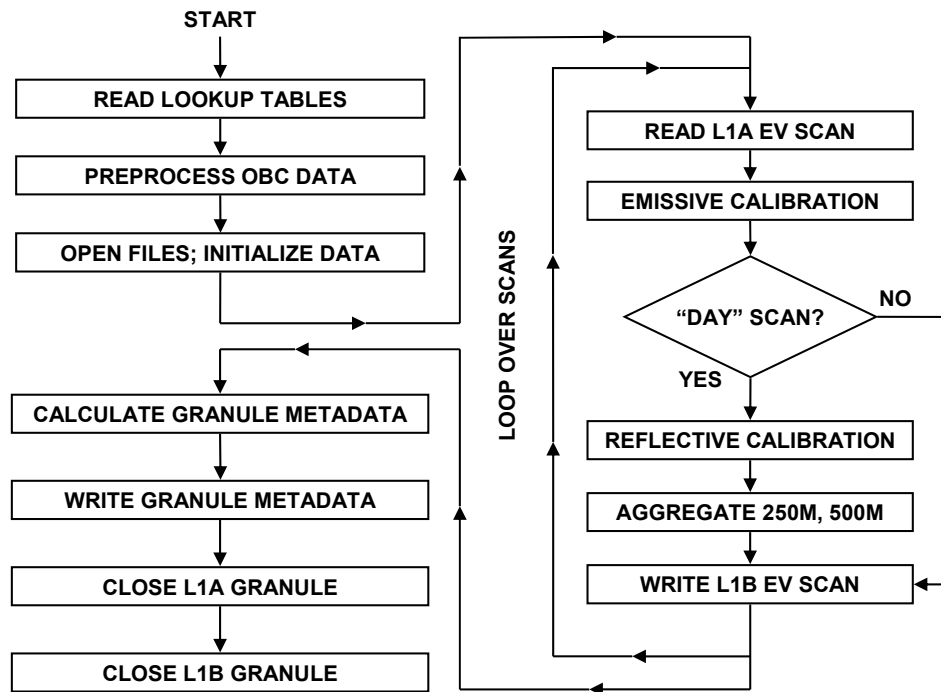
Fig. 4. MODIS Level 1B flow diagram.

Figure 4 shows the L1B data flow path. Each 5-minute granule is processed scan by scan. After pre-processing the on-board calibrator data, L1B software retrieves the L1A Earth-view (EV) DN and subtracts the average space-view (SV) background. L1B then performs TEB calibration. For day-mode data, calibration is also provided for the reflective solar bands.

Figure 5 provides a time line for Terra and Aqua post-launch code deliveries. It contains code version numbers color-coded by collection, the data day (digits are the year followed by the day of year) on which forward processing (processing newly acquired data) starts, and the LUT version numbers for each code version. The corresponding description of the nature of these L1B changes appears in Table 5. Areas of concern adequately addressed by major L1B collection improvements include treatment of non-functional or noisy detectors, optical crosstalk from Band 31 into Bands 32–36, handling the RSB time-dependent response

functions, correcting mirror-side correlated noise, and adjusting the spatial registration of the 250 and 500 meter resolution bands to the 1 km resolution bands.
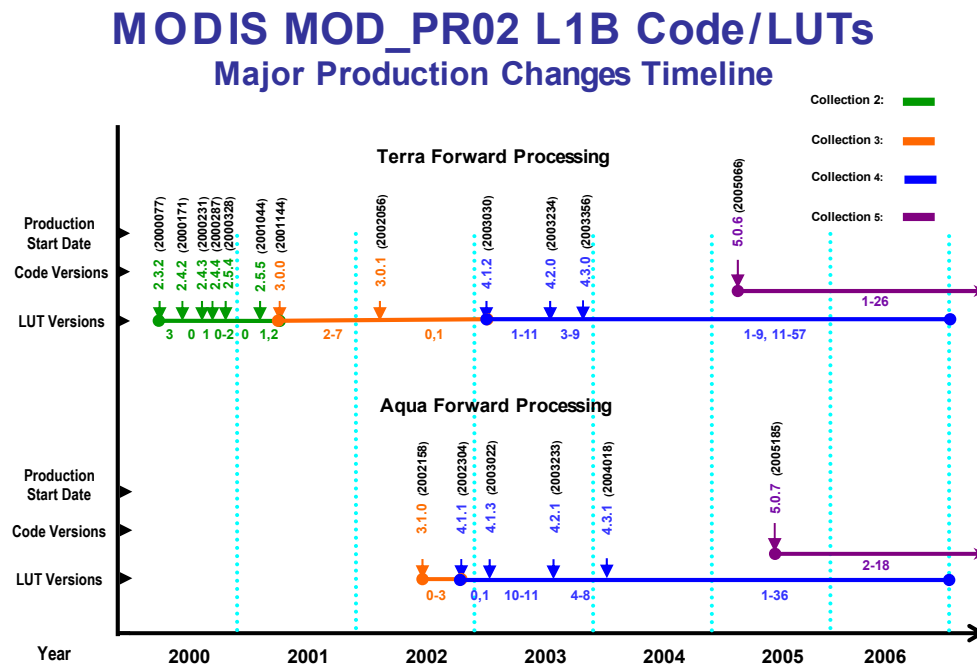
MODIS MOD_PR02 L1B Code/LUTs
Major Production Changes Timeline

Fig. 5. MODIS L1B time line for major post-launch production changes.

Table 5. MODIS L1B major post-launch updates.

TERRA Code Version	Production Start Data Day	Description of L1B Code Upgrades
2.3.2	3/17/00	First post-launch operational code; applies pre-launch calibration
2.4.2	6/19/00	Improved detection of Moon in SV port; allowed processing up to 208 scans per granule; fixed indexing bug in TEB calibration; LUTs are derived from on-orbit data
2.4.3	8/18/00	Corrected TEB pre-processing for Bands 31-36 crosstalk; interpolated data for non-functioning detectors; created time-dependent LUT architecture
2.4.4	10/13/00	New TEB algorithm to compute $<DN_{SV}>$ with moon in SV port; corrected TEB pre-processing for 40 scans before and after a sector rotation or electronics calibration; fixed indexing for SWIR out-of-band (OOB) correction; LUTs use B-side calibration
2.5.4	11/23/00	Aqua compatible code; new SWIR OOB correction algorithm
2.5.5	2/13/01	Corrected registration of aggregated images; Detector average of Esun used to compute band dependent radiance_scales
3.0.0	5/24/01	Added RSB saturation check of SV-subtracted values; revised SWIR band computation of background DN when moon is in the SV port; piece-wise linear LUT capability added
3.0.1	2/25/02	Production of 250m, 500m resolution night data made optional; LUTs

		use A-side electronics calibration
4.1.2	1/30/03	Added a de-striping algorithm; changed calculation of RVS coefficients and applied RVS piece-wise linear LUT; implemented Band 26 de-striping correction using aggregated Band 5 radiances
4.2.0	8/22/04	Selectable SWIR OOB correction "sending" band; Earth-Sun distance calculation corrected; nominal S/C altitude corrected; Nadir aperture door open/closed determination corrected
4.3.0	12/22/03	Spacecraft maneuver flag changed to key on S/C attitude
5.0.6	3/7/05	New LUT enabled Band 21 calibration with mirror-side dependence; new LUT enabled SWIR OOB correction detector dependence; corrected dimension mapping offset setting for 250 meter resolution band data; improved code portability;
AQUA Code Version	**Production Start Data Day**	**Description of L1B Code Upgrades**
3.1.0	6/7/02	Blackbody warm-up saturation corrected; applies pre-launch calibration; new blackbody temperature saturation limits
4.1.1	10/31/02	RVS correction changed to piece-wise linear
4.1.3	1/22/03	No science changes to the code
4.2.1	8/21/03	Selectable SWIR OOB correction "sending" band; implemented Band 26 de-striping correction using aggregated Band 5 radiances; Earth-Sun distance calculation corrected; nominal S/C altitude corrected; Nadir aperture door open/closed determination corrected
4.3.1	1/18/04	Used for first Collection 4 reprocessing effort; Spacecraft maneuver flag changed to key on S/C attitude
5.0.7	7/4/05	New LUT enabled Band 21 calibration with mirror-side dependence; new LUT enabled SWIR OOB correction detector dependence; corrected dimension mapping offset setting for 250 meter resolution band data; improved code portability;

5 CURRENT L1B ALGORITHM STATUS

The current L1B versions for Terra and Aqua are denoted "collection 5". Terra collection 5 was used to process data starting March 7, 2005 and Aqua collection 5 ran after July 3, 2005. Subsequently, collection 5 was used to reprocess all data prior to those dates. The L1B algorithms are based on the MODIS Algorithm Theoretical Basis Document [6]. The L1B data products are described in Ref. 7 and 8.

For each instrument, the SWIR out-of-band correction detector dependency was made more flexible by allowing selection of the "sending" RSB detectors. This ensures that problematic or non-functioning detectors are not used as sending detectors when influence coefficients are applied. The code also added mirror-side coefficient dependency to Terra and Aqua Band 21 calibration. Collection 5 also includes response versus scan angle (RVS) LUT updates for Terra based on new on-orbit deep space maneuver analysis. The RVS correction adjusts for the incoming light's angle of incidence on the MODIS mirror. This mainly affects short-wave VIS bands 3, 8, 9, and 10. In the case of forward processing, predicted calibration coefficients replaced the smooth coefficients previously used. A bug involving inaccurate geo-location of the 250m band data was also corrected in collection 5.

In 2006, there were no changes to collection 5 that affected the scientific output. Some changes were made to accommodate the transition as the MODIS Adaptive Processing System (MODAPS) assumed the data production role formerly undertaken by the Goddard Distributed Active Archive Center (GDAAC). Product files are currently distributed using the Level 1 and Atmosphere and Archive Distribution System available at http://ladsweb.nascom.nasa.gov.

The annual production of distinct MODIS code and LUT versions for Terra and Aqua are compiled in Table 6. The LUT versions are further divided into collection (C) numbers. The starting dates associated with new code collections were provided in Table 2. Table 6 only includes operational deliveries to the GDAAC or MODAPS. Over the years, 3 additional code versions and 35 special LUT versions were created upon request from MODIS scientists or MCST personnel.

Table 6. Number of MCST L1B code and look-up table (LUT) versions.

Year	Terra Code Ver.	Terra LUTs C2	Terra LUTs C3	Terra LUTs C4	Terra LUTs C5	Aqua Code Ver.	Aqua LUTs C3	Aqua LUTs C4	Aqua LUTs C5	Sum
2000	5	2	0	0	0	0	0	0	0	7
2001	2	1	5	0	0	0	0	0	0	8
2002	3	0	1	0	0	2	3	1	0	10
2003	3	0	0	19	0	3	0	17	0	42
2004	1	0	0	17	1	1	0	11	0	31
2005	2	0	0	18	10	2	0	11	7	50
2006	0	0	0	20	14	0	0	12	9	55
Sum	16	3	6	74	25	8	3	52	16	203

L1B code and LUT deliveries are made to the Science Data and Support Team, the GDAAC (until 2/2/06 for Terra collection 4, 7/5/06 for Terra collection 5, 1/17/06 for Aqua collection 4, and 3/23/06 for Aqua collection 5), the MODAPS group starting in 2006 and, upon special request, to the Rapid Response Team, the Oceans group, MCST analysts, and science team members and their colleagues. Currently, regular collection 5 LUT updates that do not significantly impact the science products occur about every 4 weeks for Terra and about every 6 weeks for Aqua. Table 7 illustrates the number of L1B code and LUT updates as a function of time for each mission. Following delivery of collection 5 code in 2005, MCST continued L1B deliveries of both collection 4 and collection 5 until December 20, 2006 for Aqua and December 27, 2006 for Terra.

Table 7. Number of MCST L1B code and look-up table (LUT) deliveries.

Submission Year	Terra Code Deliveries	Terra LUT Deliveries	Aqua Code Deliveries	Aqua LUT Deliveries	Sum
2000	5	9	0	0	14
2001	2	11	0	0	13
2002	6	12	4	30	52
2003	15	95	6	80	196
2004	2	52	3	29	86
2005	2	56	2	36	96
2006	0	45	0	25	70
Total	32	280	15	200	527

The TEB portion of the L1B flow diagram is expanded in Fig. 6. As indicated, an optical cross-talk (PC_XT) correction is applied to Bands 32-36 if the correction is switched on by the appropriate LUT. In collection 5, PC_XT is turned on for Terra, off for Aqua. L1B code uses detector gain coefficients to calculate the EV radiance for each band, detector, and frame, applying a RVS correction that is embedded in the figure's "dn to L quadratic algorithm" box. After converting the data to a scaled integer (SI), the code performs quality assurance (QA) tests and calculates an uncertainty index (UI) for each sample.
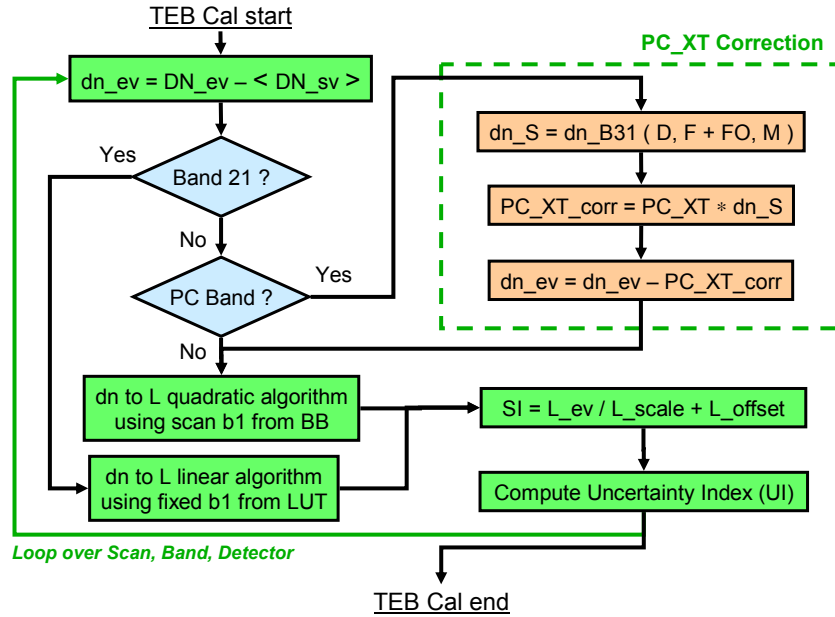
Fig. 6. Thermal emissive band L1B flow diagram.

The primary TEB product is the TOA radiance, L_{EV}. On-orbit calibration of the 160 TEB detectors distributed on the 16 TEBs is performed for each scan using a quadratic fit to the known radiance emitted by the on-board blackbody (BB). The BB warm-up, cool-down cycle allows determination of TEB radiances over temperatures ranging from 270K to 315K. The calibration equation [9] is

$$RVS_{BB}\varepsilon_{BB}L_{BB} + (RVS_{SV} - RVS_{BB})L_{SM} + RVS_{BB}(1-\varepsilon_{BB})\varepsilon_{CAV} = a_0 + b_1 dn_{BB} + a_2 dn_{BB}^2, \quad (1)$$

where ε_{BB} and ε_{CAV} are the emissivities of the BB and the instrument scan cavity, L_{SM} is the scan mirror emissivity, a_o is the offset term, the linear coefficient b_1 is computed each scan, a_2 is the quadratic term coefficient, and dn_{BB} is the observed BB DN minus the SV DN. Computing the source temperature, T_S, from Planck's equation averaged over the relative spectral response (RSR) for each detector, the source radiance follows.

$$L_S(\lambda, T_S) = \frac{\sum RSR(\lambda) \cdot Planck(\lambda, T_S)}{\sum RSR(\lambda)}. \quad (2)$$

The TOA EV radiance is analogous to Eq. (1) and is computed using

$$RVS_{EV} \cdot L_{EV} + (RVS_{SV} - RVS_{EV}) \cdot L_{SM} = a_0 + b_1 \cdot dn_{EV} + a_2 \cdot dn_{EV}^2, \quad (3)$$

where dn_{EV} is the observed EV DN minus the SV DN.

For day-mode data, output is also produced for the 20 RSBs. As diagrammed in Fig. 7, after pre-processing the L1B software retrieves the L1A EV DN and subtracts the average SV

offset. The code applies a thermal leak correction for the Terra and Aqua SWIR bands (5, 6, 7 and 26). The radiance from one of the thermal emissive bands is used as a surrogate for the leak. Therefore, the thermal bands are calibrated prior to the reflective bands. The L1B RSB calibration module also applies temperature corrections and a time-dependent correction for the MODIS RVS. The reflectance factor is computed using scaling coefficients which are determined offline from the SD/SDSM calibration and normalized by the square of the Earth-Sun distance (ESD). Analogous to TEB processing, the RSB module performs QA tests and calculates an uncertainty index for each sample.

RSB Cal start

SWIR Correction

dn_ev = DN_ev – DN_obc_avg

SWIR Band ? →Yes→ dn_X = dn_B25 or dn_B28 (D, F, M)

SWIR_corr = x_0 + x_1 ∗ dn_X + x_2 ∗ dn_X²

dn_ev = dn_ev - SWIR_corr

No

dn* = dn_ev ∗ Temp_corr / RVS

Refl = m0 + (m1 / ESD²) ∗ dn*

SI = dn** / Count_scale + Count_offset

dn** = Refl / (Max(m1 / ESD²))

Compute Uncertainty Index (UI)

Loop over Scan, Band, Detector, Sub-frame

RSB Cal end
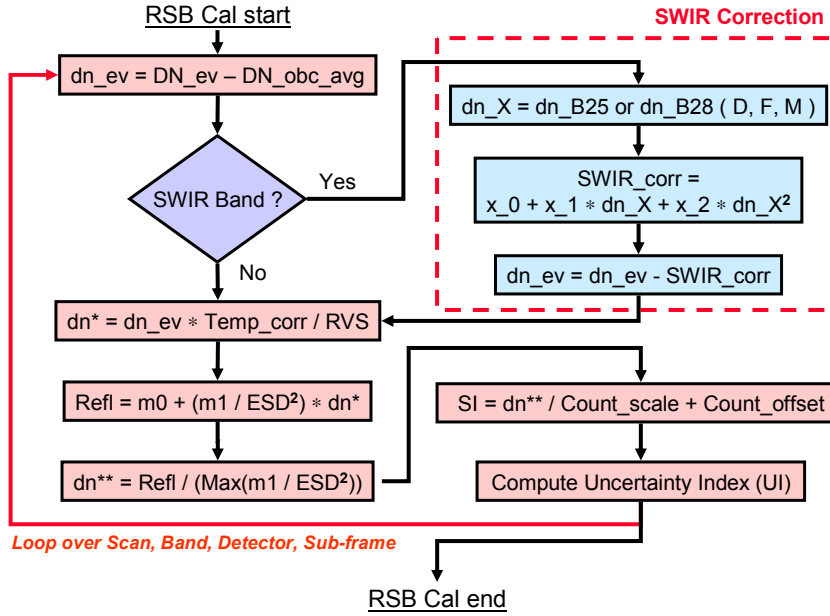
Fig. 7. Reflective solar band L1B flow diagram.

The primary product of the MODIS L1B for RSB is the EV TOA reflectance factor, $\rho_{EV} \cos(\theta_{EV})$, calculated using a linear algorithm by

$$\rho_{EV} \cos(\theta_{EV}) = m_1 \cdot dn^*_{EV} \cdot d^2_{ES} , \qquad (4)$$

where ρ_{EV} is the Earth scene bi-directional reflectance factor (BRF), θ_{EV} is the solar zenith angle of the EV pixel, m_1 is the calibration coefficient which is supplied by a time-dependent LUT derived and updated on-orbit from the SD/SDSM calibration, dn^*_{EV} is the sensor's EV response corrected for the effects of instrument background, temperature, and viewing angles, and d_{ES} is the Earth-Sun distance in AU at the time of the EV observation. dn^*_{EV} is obtained from the EV and Space view averaged offset by

$$dn^*_{EV} = \left(DN_{EV} - \overline{DN_{SV}} \right)\left(1 + k_{inst}\Delta T\right) / RVS , \qquad (5)$$

where the coefficient k_{inst} is the rate of gain-change due to temperature and is provided by a LUT determined pre-launch, $\Delta T_{Inst,EV}$ is the temperature difference relative to the nominal pre-launch calibration temperature, and RVS is the Response Versus Scan angle (RVS) which

is provided by a time-dependent LUT determined pre-launch and updated on-orbit using the SD, Moon, SRCA, and EV data.

For application convenience, MODIS L1B also generates a radiance product for the reflective solar bands. It can be derived from the primary reflectance factor using the following expression,

$$L_{EV} = \frac{E_{SUN}}{\pi} \rho_{EV} \cos(\theta_{EV}) \,, \tag{6}$$

where E_{SUN} is the solar irradiance [10-12], weighted by each detector's RSR.

Data quality flags are assigned to each scan. The performance of the 490 detectors on each MODIS instrument is tracked daily and expressed in a time-dependent detector QA LUT. The Detector Quality Flag LUTs for Terra and Aqua characterize individual detector quality. The meaning of each bit is provided in Table 8. Additional QA flag bits are described in Table 9.

Table 8. Detector quality assurance look-up table structure and meaning.

Bit #	Meaning	Band Criteria
Bit 0	Noisy Detector	NEdL (Noise equivalent delta radiance at Ltyp (typical radiance) > 2 times mission spec.
Bit 1	Non-Functional Detector	Non-responsive detector
Bit 2	Out-of-Family Gain	Bands 1-19,21,26: Gain deviates by > 10% from median gain. Other bands TBD.
Bit 3	Dynamic Range	Saturates before mission specification Lmax
Bit 4	Detector DN saturates on calibration source	RSB: Expected DN saturates on illuminated, unscreened Solar Diffuser. TEB: Expected DN saturates on 300K blackbody.
Bit 5	High calibration fit residuals	> 1% deviation from linear or quadratic fit Observed on pre-flight data within calibration range
Bit 6	Electrical or Optical Crosstalk	Residual Crosstalk observed on orbit
Bit 7	TBD	TBD

Table 9. Bit quality assurance flags and descriptions.

Bit #	Description (condition that causes bit to be set to 1)
Bit 0	Moon within defined limits of Space View Port (the moon was found to be in the SV keep-out box for at least one detector of at least one MODIS band on this scan)
Bit 1	Spacecraft Maneuver
Bit 2	Sector Rotation
Bit 3	Negative Radiance Beyond Noise Level (at least 1 thermal emissive band pixel has a radiance value less than NEdL on this scan)
Bit 4	Photo-Conductive bands Electronic calibration (Ecal) "on"
Bit 5	Photo-Voltaic bands Ecal "on"
Bit 6	Solar Diffuser (SD) Door Open
Bit 7	SD Screen Down
Bit 8	Nadir Aperture Door closed

Bit #	Description (condition that causes bit to be set to 1)
Bit 9	SDSM "on"
Bit 10	Radiative cooler Heaters "on"
Bit 11	Day mode bands telemetered at night (an algorithm using the SD Sun azimuth and SD Sun zenith angles is used to flag situations where the Scan type is "Day" but the spacecraft is actually in spacecraft night.).
Bit 12	Linear Emissive Calibration - This value is set to 0. This bit is effectively unused at the present time.
Bit 13	DC Restore Change (the FPA DCR offset value for any detector changed from the value of the last scan)
Bit 14	(unused)
Bit 15	BB Heater "on" (either heater A or B is on)
Bit 16	Missing Previous L1A Granule.
Bit 17	Missing Subsequent L1A Granule.
Bit 18-19	SRCA calibration mode
Bit 20	Moon within the SV keep-out box for Reflective Solar bands (the moon was found to be in the space-view keep-out box for at least one detector of at least one reflective Solar band on this scan)
Bit 21	Moon within the SV keep-out box for Emissive bands (the moon was found to be in the space-view keep-out box for at least one detector of at least one thermal emissive band on this scan)
Bit 22	All space-view data bad for any Reflective Solar band (the algorithm could not compute a valid electronic background level from SV data for at least one detector of at least one reflective Solar band for this scan).
Bit 23	All blackbody data bad for any Reflective Solar band (the algorithm could not compute a valid electronic background level from BB data for at least one detector of at least reflective Solar band for this scan).
Bit 24	Dropped scan(s) between previous granule and granule being calibrated. If 5 or fewer scans are dropped between the granules, the previous granule will be used for emissive calibration; if more than 5 are dropped, it will not be used.
Bit 25	Dropped scan(s) between granule being calibrated and subsequent granule. If 5 or fewer scans are dropped between the granules, the subsequent granule will be used for emissive calibration; if more than 5 are dropped, it will not be used.
Bit 26	SCI_ABNORMAL flag
Bit 27-31	Reserved for future use

Within Bit 18-19:

Bit 18	Bit 19	Calibration Mode	
0	0	Radiometric	(0)
0	1	Spatial	(1)
1	0	Spectral	(2)
1	1	Undetermined	(3)

The calibrated EV data are stored as SI in science data sets (SDS). A set of band-dependent scale and offset terms provided in the L1B output as SDS attributes are used to reconstruct the radiance and reflectance values. The MODIS Level 1B Product User's Guide [13] describes this process.

The calibrated Earth observations are stored as scaled integers (SI). These are converted to the scene TOA radiances or reflectance factors. For the TEB radiance,

$$Radiance = radiance\_scales * (SI - radiance\_offsets) . \qquad (7)$$

For the RSB reflectance factor,

$$Reflectance = reflectance\_scales * (SI - reflectance\_offsets) . \qquad (8)$$

After the radiometric uncertainty calculation, the uncertainty is written to the L1B products in terms of the Uncertainty Index (UI) for each pixel, with an integer ranging from 0 to 15. The UI is computed in the L1B using the expression

$$UI = scaling\_factor[B] \cdot ln\left(\frac{RSS}{specified\_uncertainty[B]}\right). \qquad (9)$$

Here, RSS indicates the Root-Sum-Square uncertainty, computed dynamically for each pixel in each scan. The use of log scaling allows a broad range of uncertainty to be covered while an adequate resolution for small uncertainties is still retained. LUTs provide the band dependent scaling factor[B] and specified uncertainty[B] values.

SDS attributes "specified uncertainty" and "scaling factor" in Eq. (10) are used to convert the UI to the percentage uncertainty. This relationship is tabulated in Table 10. Additional information is provided by MCST [13].

$$Uncertainty\ (\%) = Specified\_uncertainty \cdot exp(\frac{UI}{Scaling\_factor}) \qquad (10)$$

Table 10. L1B uncertainty index (UI) mapped to uncertainty in percent.

UI	Bands 1-4, 8-19	Bands 5, 6, 7, 26	Band 20	Band 21	Bands 22-25, 27-30, 33-36	Bands 31, 32
0	1.50	1.50	0.56	2.50	0.50	0.38
1	1.73	1.83	0.69	3.21	0.64	0.48
2	2.00	2.24	0.84	4.12	0.82	0.62
3	2.30	2.73	1.02	5.29	1.06	0.79
4	2.66	3.34	1.25	6.80	1.36	1.02
5	3.06	4.08	1.53	8.73	1.75	1.31
6	3.53	4.98	1.87	11.20	2.24	1.68
7	4.08	6.08	2.28	14.39	2.88	2.16
8	4.70	7.43	2.79	18.47	3.69	2.77
9	5.43	9.07	3.40	23.72	4.74	3.56
10	6.26	11.08	4.16	30.46	6.09	4.57
11	7.22	13.54	5.08	39.11	7.82	5.87
12	8.33	16.53	6.20	50.21	10.04	7.53
13	9.61	20.20	7.57	64.48	12.90	9.67
14	11.08	24.67	9.25	82.79	16.56	12.42
15	≥ 12.79	≥ 30.13	≥ 11.30	≥106.30	≥ 21.26	≥ 15.95

6 POTENTIAL FUTURE IMPROVEMENTS AND LESSONS LEARNED

MCST will continue to strive for optimum absolute calibration accuracy by supplementing the use of data from on-board calibrators with input from ground truth and inter-instrument comparisons. Operational quality assurance reporting may be enhanced. A future collection 6 L1B may implement new algorithms to improve the science products. In addition to supplying time-dependent LUT updates, MCST may determine the noise level on a finer time and spatial basis called a subframe (smaller than a pixel) basis. Terra Collection 6 may address the issue of electronic crosstalk in subframe 1 of band 2, detectors 29 and 30. As the MODIS ages and the possibility of instrument component failure increases, Collection 6 code might add the capability to handle non-functional BB thermistors.

Ongoing Terra RVS studies could lead to the adoption of an alternative approach for handling this instrument characteristic. Terra collection 6 may include the flexibility to apply a detector-dependent RVS instead of the current RVS which is computed as the average over all good detectors in each band. Another issue under study is the possible transition from interpolating values for non-functional detectors to assigning a fill value. MCST may also attempt a more consistent treatment of TEB calibration coefficients between Terra and Aqua MODIS. Also, recent advances in handling Aqua long-wave infrared data (Band 33-36) and an apparent mirror-side correlated noise on Terra may result in Terra Collection 6 improvements. Band 7 striping noted by the land science team may be mitigated either in L1B or downstream in Collection 6.

Technical lessons learned from on-orbit MODIS performance have been presented [14]. Ref. 7 describes other general lessons learned during L1B development. The value of on-orbit calibration, instrument characterization, and quality assurance is paramount. As experience is gained and the instrument response is studied, code imperfections and inefficiencies will surface. Timely data analysis enables rapid upgrades to the software.

Periodic data reprocessing is needed. The MODIS project realized the benefit of adding flexibility to the L1B software. One example of this flexibility is the creation of separate Terra and Aqua codes to handle instrument performance differences. Another illustration is enabling data processing in the absence of time-ordered data within each processing period. A third example is the introduction of time-dependent LUTs and the addition of piece-wise linear interpolation for the LUTs.

Consistency is desirable. MODIS Terra and Aqua codes and LUTs are managed under a common configuration management system. Established policy mandates that all code changes and significant LUT updates are presented to the MODIS Science Working Group (MSWG) before implementation. The MSWG contains representatives from ocean, atmosphere, and land disciplines. All code and LUT modifications are tested prior to delivery using an established sequence of procedures. To avoid single-point failures, it is preferred that two persons build the LUT files independently and compare results before submission. However, as experience was gained and personnel resources diminished, this procedure was modified. Currently, one person builds the LUTs and an independent review of each build is conducted.

Detailed documentation and updates are necessary to describe the function and application of the L1B code for each collection. The MODIS project produced and periodically updates a MODIS Level 1B Product User's Guide [13], MODIS Level 1B Products Data Dictionary [15], MODIS LUT Information Guide [16], and extensive documentation on the MCST home page [3].

7 SUMMARY

MODIS, a key instrument on NASA's EOS missions, is currently operating on both the Terra and Aqua spacecraft. MODIS provides global observations with complementing morning and afternoon observations of the Earth's land, oceans, and atmosphere. The two MODIS instruments are nearly identical, allowing a common calibration approach. Special treatments have been added in the code to account for differences in the two sensors.

MODIS observations span the VIS to LWIR regime, using 36 bands taking observations at 250m, 500m, and 1km nadir spatial resolutions. The mature, validated MODIS L1B algorithms used to generate calibrated L1B products have undergone improvements in each "collection". Updates that account for time-dependent changes in sensor performance are implemented via numerous L1B LUTs. MODIS instrument calibration and characterization, current instrument status, L1B code changes, and LUT updates, are described on the MCST web page [3].

Acknowledgments

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